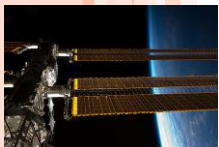


RECAPTURING A FUTURE FOR SPACE EXPLORATION: LIFE AND PHYSICAL SCIENCES RESEARCH FOR A NEW ERA

WHAT ARE THE KEY SCIENTIFIC CHALLENGES THAT LIFE AND PHYSICAL SCIENCES RESEARCH IN SPACE MUST ADDRESS IN THE NEXT 10 YEARS?



"In the context of extraordinary advances in the life and physical sciences and with the realization that national policy decisions will continue to shift near-term exploration goals, the committee focused on surveying broadly and intensively the scientific issues necessary to advance knowledge in the next decade. Such a task is never easy; it relies on interpolation and extrapolation from existing knowledge sources and educated assumptions about new developments. The committee grappled with all of these issues as well as the thorny problem of how to organize the scientific efforts themselves procedurally so that they would flourish in the next decade".



Betsy Cantwell
Wendy Kohrt

Decadal Survey on Biological and Physical Sciences in Space
National Academy of Sciences

DECADAL SURVEYS

- One principal means by which NASA's Science Mission Directorate engages the science community is through the National Research Council (NRC).
 - The NRC conducts studies that provide a science community consensus on key questions posed by NASA and other U.S. Government agencies. The broadest of these studies in NASA's areas of research are decadal surveys.
 - As the name implies, NASA and its partners ask the NRC once each decade to look out ten or more years into the future and prioritize research areas, observations, and notional missions to make those observations.
 - Decadal surveys have been carried out in the areas of astronomy, planetary science, heliophysics, and Earth science
- These decadal provide federal agencies like NASA with the basis for planning the next decades science portfolios
- Cost estimates and budget recommendations are now required for most decadal surveys
- Community input is a strong part of all decadal studies
 - White paper submission
 - We requested White Papers detailing recommendations from the community for research topics that either enable exploration capabilities, or are enabled by access to the low-gravity environment of space.
 - Town Hall meetings
- Our largest challenge has been to continue to move forward in our deliberations in the face of change and uncertainty
 - A great deal was possible, despite this uncertainty

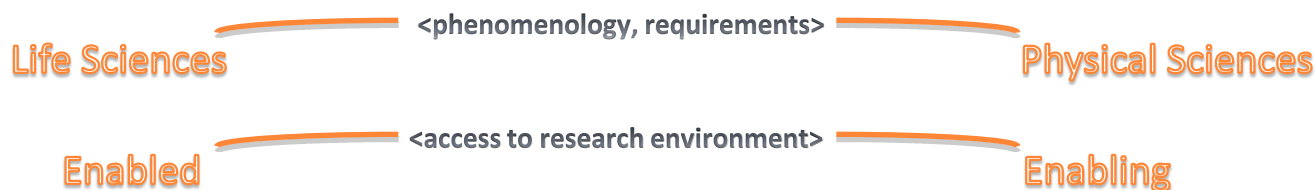


THE DECADAL SURVEY

- NASA asked the National Academy of Sciences to:

Define research areas that:

- Enable exploration missions
- Are enabled by exploration missions
- Define and prioritize an integrated life and physical sciences research portfolio and associated objectives;
- Develop a timeline for the next decade for these research objectives and identify dependencies between the objectives;
- Explain how the objectives could enable exploration activities, produce knowledge, or provide benefits to space and other applications;
- Identify terrestrial, airborne, and space-based platforms and facilities that could most effectively achieve the objectives;
- Identify potential research synergies between NASA and other US government agencies, as well as with commercial entities and international partners; and
- Identify potential research objectives beyond 2020.



PANELS FOR THIS DECADAL STUDY

Steering Committee

Life Sciences

- Animal & Human Biology
- Plant & Microbial Biology
- Human & Behavioral Health

Translation

- Integrative & Translational Research for the Human System
- Translation to Space Exploration Systems

Physical Sciences

- Fundamental Physical Sciences
- Applied Physical Sciences



KEY CONCEPT FROM INITIAL DISCUSSIONS

○ Translational Research

- A number of factors have combined to impede the flow of information between basic science and complex applications. Adapting the NIH model,
 - We focus on *translational research* to try and remove these obstacles and overtly facilitate and expedite the practical application of scientific discoveries
 - Translating knowledge from laboratory discoveries to operational conditions is a challenging, two-fold task:
 - *Horizontal integration requires multi- and trans-disciplinary approaches to complex problems;*
 - *Vertical translation requires meaningful interactions among basic, preclinical, and/or applied scientists to translate fundamental discoveries into improvements in the health of crew members or the functioning of complex systems in space.*
 - Strong emphasis placed on the need for effective coupling of biological, physical and engineering problem-solving strategies. By its nature, this process involves engineers understanding and applying the recent findings of research scientists and research scientists working in the parameter space of specific mission categories.



KEY CONCEPT FROM INITIAL DISCUSSIONS

○ Research Infrastructure

- The capabilities provided by ISS are vital to answering many of the most important research questions detailed in the decadal survey. The ISS provides a truly unique platform for research,
 - But it is only one component of a robust program. Other platforms and elements of research infrastructure will be important, including those that are ground based.
- Flight research is generally part of a continuum of efforts that extend from laboratories and analog environments on the ground, through other low-gravity platforms as needed and available, and eventually into extended-duration flight.
 - Like any process of scientific discovery this effort is iterative, and further cycles of integrated ground-based and flight research are likely to be warranted as understanding of the system under study evolves.



EXPLORATIONS SYSTEM ENDPOINTS THAT CAN MOTIVATE RESEARCH

Exploration Systems

The Human System

- Risk Reduction Needs
 - Space Radiation
 - Human Health Countermeasures
 - Exploration Medical Capability
 - Space Human Factors & Habitability
 - Behavioral Health & Performance

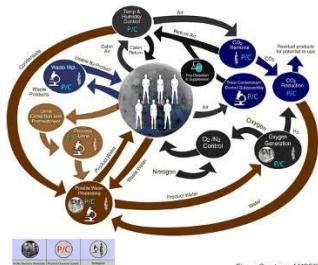


Figure Courtesy of MSFC

- Human Requirements
 - Crews must live & work safely
 - Medical standards
 - Validated countermeasures
 - Health management
 - Human factors
 - Environmental health
 - Food technology
 - Tools and strategies that mitigate behavioral & performance risks

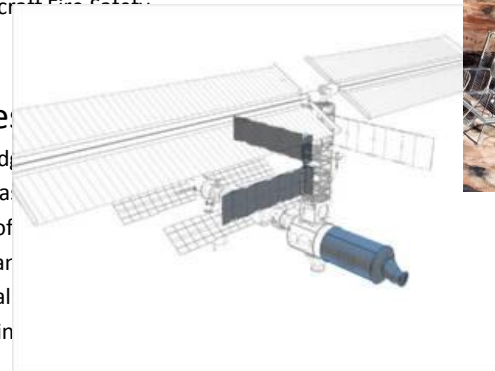
Life Support & Habitation



- Behavioral Health
- Anthropometry & Ergonomics
- Radiation Protection
- Toxicity of Atmospheric Contaminants
- Biological Life Support
- High Performance Materials
- Materials Processing & Recycling
- Multiphase Flows
- Spacecraft Fire Safety

In-Situ Resource Utilization

- Sharp-edged Granular Media
- Multiphase Flows
- Mixing of Granular Media
- Heat Transfer
- Chemical Processes
- Processing



System Function Needs

- Power Generation & Storage
- Space Propulsion
- Life Support
- Hazard Control
- Material Production & Storage
- Construction & Maintenance



Surface Mobility & Extravehicular Activity

- Anthropometry & Ergonomics
- Radiation Monitoring & Protection
- Sharp-edged Granular Media
- High Performance Materials
- Multiphase Flow



EXPLORATION CHALLENGES THAT SCIENCE CAN ADDRESS

- Gravity-Dependent Phenomena

- Interfacial phenomena
- Multiphase Flow
- Heat transfer
- Solidification
- Chemical Transformation
- Behavior of Granular Materials



- Maintaining Human Health

- Human Physiology
- Medical Capability
- Microbiology
- Radiation
- Behavior & Performance
- Habitation & Environment
- Lunar Dust



- Cryogenic Fluid & Thermal Management

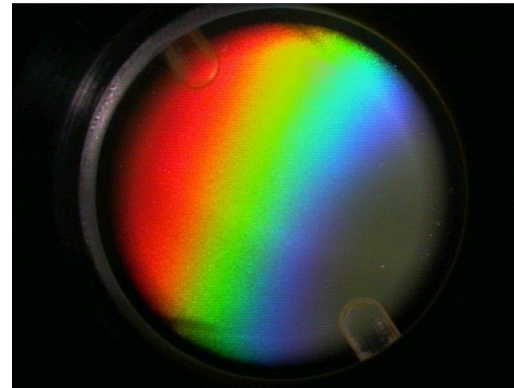
- Mixing of Cryogenic Fluids
- Partial Gravity
- Multiphase Flows
- Heat Transfer
- Materials Development



SCIENCE CHALLENGES THAT EXPLORATION SYSTEMS CAN ADDRESS

- Enabling Scientific Discovery

- Fundamental physics
- Fluid Flow
- Granular Media
- Heat Transfer
- High Performance Materials



- Plant Growth
- Understanding Microbes in Extreme Environments
- Human Factors



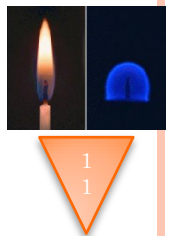
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- **Wendy M. Kohrt**, *co-chair*
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- **Benjamin D. Levine**
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Northwestern University
- **Dr. Robert V. Duncan** - Fundamental Physical Sciences
Missouri University of Science and Technology
- **Dr. Thomas J. Balkin** - Human Behavior & Mental Health
Walter Reed Army Institute of Research
- **Dr. James A. Pawelczyk** - Cross-Cutting Research for the Human System
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- **Dr. Terri Lomax** - Plant & Microbial Biology
North Carolina State University
- **Dr. James P. Bagian** - Translation to Space Exploration Systems
Veterans Health Administration



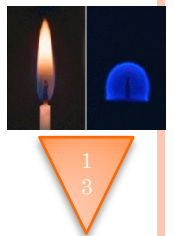
THE BOTTOM LINE

“Although its review has left it deeply concerned about the current state of NASA’s life and physical sciences research, the Committee for the Decadal Survey on Biological and Physical Sciences in Space is nevertheless convinced that a focused science and engineering program can achieve successes that will bring the space community, the U.S. public, and policymakers to an understanding that we are ready for the next significant phase of human space exploration. The goal of this report is to lay out steps whereby NASA can reinvigorate its partnership with the life and physical sciences research community and develop a forward-looking portfolio of research that will provide the basis for recapturing the excitement and value of human spaceflight—thereby enabling the U.S. space program to deliver on new exploration initiatives that serve the nation, excite the public, and place the United States again at the forefront of space exploration for the global good.”



REPORT PREPARATION

- The report is divided into 13 chapters that summarize the deliberations of the committee and input of the seven panels of experts.
- Information, perspectives, and advice were obtained from the general public and numerous experts in the field
 - Various representatives of past and current NASA programs, experts from a range of disciplines, and speakers from private companies that are increasingly involved in space exploration all provided briefings to the panels and the committee.



REPORT SYNOPSIS

- The report is a highly integrated effort by the committee and its panels.
 - Differences exist between chapters. Potential metrics were shared and discussed but each panel applied the specific metrics that were most appropriate for its discipline
 - The metrics were aggregated and synthesized into a common set of criteria against which all of the highest priority recommendations were mapped
 - Each panel chapter (Chapters 4 through 10) contains:
 - review of the current status of knowledge
 - assessment of gaps in knowledge
 - recommendations to address gaps
 - recommendations considered to be of the highest priority; and
 - discussion of the timeframe, facilities, and platforms needed to support the recommended research.
- Research was selected independently of the consideration of what platform should be used and whether that platform was available. Platform needs were identified after high-priority research was identified.



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- 12 - ESTABLISHING A LIFE AND PHYSICAL SCIENCES RESEARCH PROGRAM: PROGRAMMATIC ISSUES
- 13 - ESTABLISHING A LIFE AND PHYSICAL SCIENCES RESEARCH PROGRAM: AN INTEGRATED MICROGRAVITY RESEARCH PORTFOLIO



PROGRAMMATIC ISSUES₁

The committee identified critical needs for the successful renewal of research endeavors in life and physical sciences. These include:

- Elevating the priority of life and physical sciences research in space exploration
 - Central to NASA's exploration mission and embraced throughout the agency as an essential translational step in the execution of space exploration missions
 - Integral component of spaceflight operations, including astronauts' participation
 - Collection and analysis of a broad array of astronaut data; legal concerns about confidentiality could be addressed by the DHHS SACHRP
- Establishing a stable and sufficient funding base
 - Balanced between intramural and extramural activities to support a sufficiently robust extramural research program
 - Sustained and strengthened collaborations with other sponsoring agencies



PROGRAMMATIC ISSUES₂

- Improving the process for solicitation and review of high-quality research
 - Regularly issued solicitations including broad research announcements, targeted research announcements, and team research announcements that specifically foster multidisciplinary translational research.
 - A review process for extramural and intramural research that is transparent and accountable for prioritization of intra- and extramural investigations.
- Rejuvenating a strong pipeline of intellectual capital through training and mentoring programs
 - Educational programs and training opportunities to expand the pool of graduate students, scientists, and engineers who will be prepared to improve the translational application of fundamental and applied life and physical sciences research to space exploration needs.



PROGRAMMATIC ISSUES₃

- Linking science to mission capabilities through multidisciplinary translational programs
 - Long-term strategic plan for maximizing team research opportunities to accelerate the trajectory of research discoveries and improve the translation to solutions for the complex problems associated with space exploration.
 - Improved central information networks to facilitate data sharing with and analysis by the life and physical science communities.
 - Improved the access of the scientific community to samples and data collected from astronauts; concerns regarding the confidentiality could be addressed by the DHHS SACHRP.
- Developing commercial sector interactions to advance science, technology, and economic growth
 - Foster interactions with the commercial sector, particularly commercial in a manner that addresses research needs, with attention to such issues as control of intellectual property, technology transfer, conflicts of interest, and data integrity.

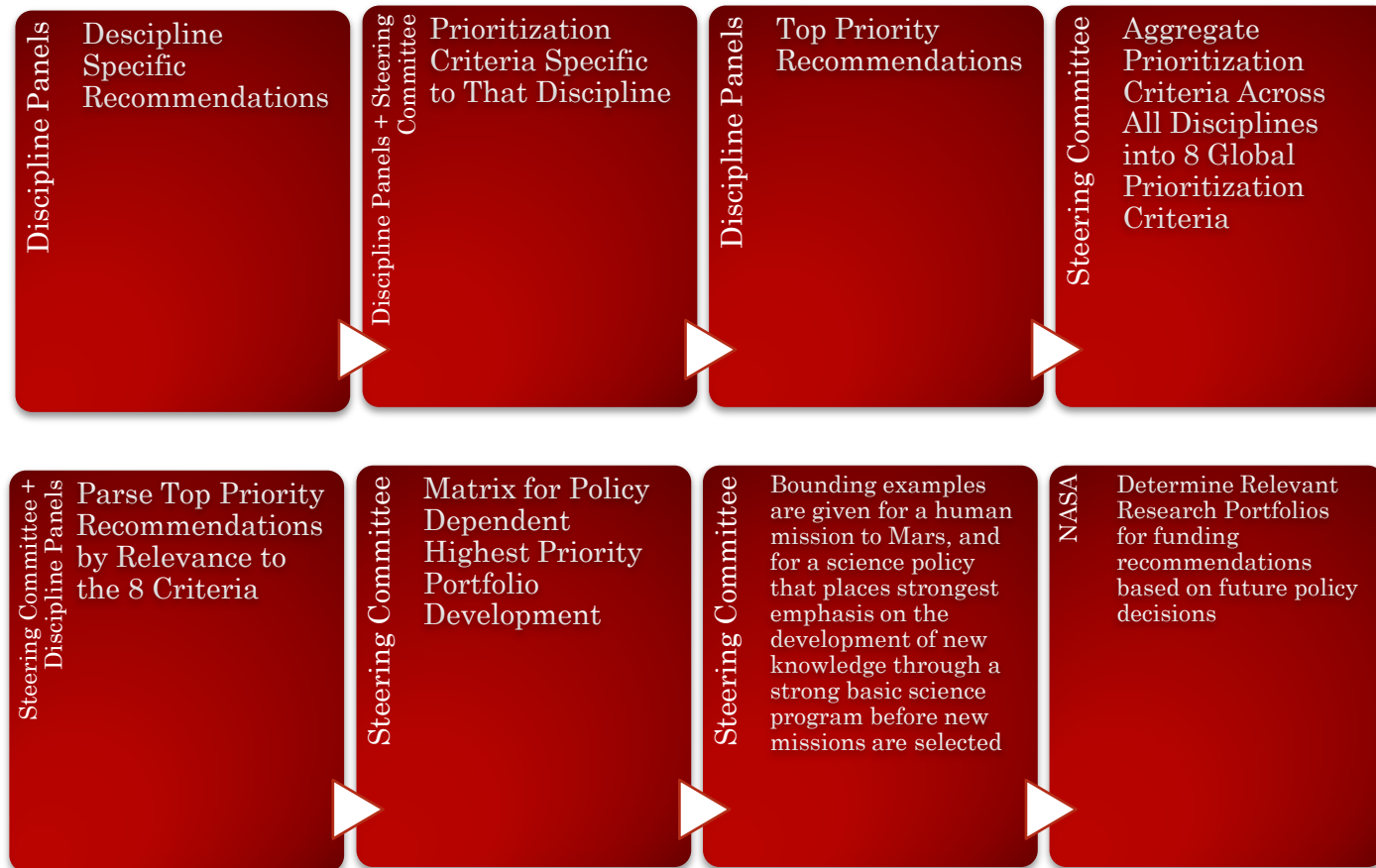


PROGRAMMATIC ISSUES₄

- Administrative oversight of life and physical sciences research
 - Leadership with both true scientific gravitas and a sufficiently high level in the overall organizational structure at NASA is needed to ensure that there will be a “voice at the table” when the agency engages in difficult deliberations about prioritizing resources and engaging in new activities.
 - The successful renewal of a life and physical sciences research program will depend on strong leadership with a unique authority over a dedicated and enduring research funding stream.
 - It is important that the positioning of leadership within the agency allows both the conduct of the necessary research programs as well as interactions, integration, and influence within the mission-planning elements that develop new exploration options.



ESTABLISHING AN INTEGRATED RESEARCH PORTFOLIO



PRIORITIZATION CRITERIA

Eight prioritization criteria were used to capture the potential value of the results of research. The committee did not weight these criteria, a step that would require assumptions about policy decisions not yet made, or subject to change in the future

- Prioritization Criteria 1: The extent to which the results of the research will reduce uncertainty about both the benefits and the risks of space exploration (*Positive Impact on Exploration Efforts, Improved Access to Data or to Samples, Risk Reduction*)
- Prioritization Criteria 2: The extent to which the results of the research will reduce the costs of space exploration (*Potential to Enhance Mission Options or to Reduce Mission Costs*)
- Prioritization Criteria 3: The extent to which the results of the research may lead to entirely new options for exploration missions (*Positive Impact on Exploration Efforts, Improved Access to Data or to Samples*)
- Prioritization Criteria 4: The extent to which the results of the research will provide full or partial answers to grand science challenges that the space environment provides a unique means to address (*Relative Impact Within Research Field*)
- Prioritization Criteria 5: The extent to which the results of the research are uniquely needed by NASA, as opposed to any other agencies (*Needs Unique to NASA Exploration Programs*)
- Prioritization Criteria 6: The extent to which the results of the research can be synergistic with other agencies' needs (*Research Programs That Could Be Dual-Use*)
- Prioritization Criteria 7: The extent to which the research must use the space environment to achieve useful knowledge (*Research Value of Using Reduced-Gravity Environment*)
- Prioritization Criteria 8: The extent to which the results of the research could lead to either faster or better solutions to terrestrial problems or to terrestrial economic benefit (*Ability to Translate Results to Terrestrial Needs*)



ESTABLISHING A PORTFOLIO

- Facility and platform requirements are identified for each of the various areas of research discussed in this report. Free-flyers, suborbital spaceflights, parabolic aircraft, and drop towers are all important platforms. Eventually, access to lunar and planetary surfaces will make it possible to conduct critical studies in the partial gravity regime and will enable testbed studies of systems that will have to operate in those environments.
- Some of the key issues to be addressed in the integrated research portfolio are
 - The effects of the space environment on life support components
 - The management of the risk of infections to humans
 - Behavior having an impact on individual and group functioning,
 - Risks and effects of space missions on human physiological systems
 - Applied fluid physics and fire safety
 - Translational challenges arising at the interface bridging basic and applied research in both life and physical sciences



TABLE 13.2 Highest-Priority Recommendations That Provide High Support in Meeting Each of Eight Specific Prioritization Criteria

	Prioritization Criteria							
	(1) Positive Impact on Exploration Efforts, Improved Access to Data or to Samples, Risk Reduction	(2) Potential to Enhance Mission Options or to Reduce Mission Costs	(3) Positive Impact on Exploration Efforts, Improved Access to Data or to Samples	(4) Relative Impact Within Research Field	(5) Needs Unique to NASA Exploration Programs	(6) Research Programs That Could Be Dual-Use	(7) Research Value of Using Reduced-Gravity Environment	(8) Ability to Translate Results to Terrestrial Needs
Life Sciences	P2, P3, B1, B2, B3, B4, AH1, AH2, AH3, AH5, AH6, AH7, AH8, AH9, AH10, AH11	P3, B1, B2, B3, B4, AH6, AH9, AH10, AH11	P3, B4, AH1, AH2, AH3, AH5, AH6, AH7, AH8, AH9, AH10, AH11	P1, P2, B3, B4, AH9, AH10, AH11, AH16	P1, P2, P3, AH1, AH2, AH3, AH4, AH5, AH6, AH7, AH8, AH9, AH10, AH11, AH16	B1, B2, B3, B4, AH1, AH2, AH3, AH4, AH5, AH6, AH7, AH9, AH10	P1, B1, B4, AH12, AH16	B1, B2, B3, B4, AH1, AH2, AH3, AH4, AH5, AH6, AH7
Translational Life Sciences	CCH2, CCH4, CCH7	CCH2, CCH4, CCH6, CCH7	CCH2, CCH4, CCH6, CCH7, CCH8	CCH2, CCH6	CCH1, CCH2, CHH3, CCH6, CCH7, CCH8		CCH1, CHH2, CHH3, CCH7, CCH11	
Physical Sciences	AP1, AP4, AP6, AP8, AP11	AP1, AP2, AP10, AP11	AP1, AP2, AP3, AP10, AP11	FP1, FP2, FP3, AP5, AP7, AP8, AP9	AP1, AP2, AP3, AP4, AP6, AP11	AP7, AP8, AP9, AP10	FP1, FP2, FP3, FP4, AP1, AP2, AP5, AP6, AP7, AP9	AP1, AP2, AP7, AP8, AP9
Translational Physical Sciences	TSES1, TSES2, TSES3, TSES14	TSES1, TSES3, TSES5, TSES10	TSES14		TSES2, TSES3, TSES4, TSES5, TSES6, TSES7, TSES12, TSES13, TSES14, TSES16	TSES10, TSES11, TSES12	TSES1, TSES2, TSES3, TSES4, TSES5, TSES12, TSES13, TSES14, TSES15, TSES16	TSES10

NOTE: Identifiers are as listed in Table 13.1 and correspond with the recommendations listed there and also presented with clarifying discussion in Chapters 4 through 10.



POLICY EXAMPLE — HUMANS TO MARS

Goal: send humans to Mars



Prioritization Criteria #1 and #2 will be the most important functions in prioritizing the research to support this policy, and the recommendations associated with these priorities must find a way to be supported in an integrated program with clear translational end-points. Secondly, Prioritization Criteria #3 and #5 will also have to be taken into consideration to achieve the science necessary for this policy goal.

Criterion #1: The extent to which research developments will reduce uncertainty about both benefits and risks of space exploration (Impact on Exploration Efforts, Results in Improved Access to Data or to Samples, Risk Reduction)

Relevant research recommendations

Life sciences: P2, P3, B1, B2, B3, B4, AH1, AH2, AH3, AH5, AH6, AH7, AH8, AH9, AH10, AH11
Life sciences translational: CCH2, CCH4, CCH7
Physical sciences: AP1, AP4, AP6, AP8
Physical sciences translational: TSES1, TSES2, TSES3, TSES14

The efficacy of bisphosphonates should be tested in an adequate population of astronauts on the ISS during a 6-month mission.

Criterion #2: The extent to which information gained from investment in research funding will reduce the costs of space exploration (Potential to Enhance Mission Options or Mission Costs)

Relevant research recommendations

Research should be conducted in support of zero-boiloff propellant storage and cryogenic fluid management. Physical sciences research includes advanced insulation materials research, active cooling, multi-phase flows, and capillary effectiveness (T2), as well as active and passive storage, fluid transfer, gauging, pressurization, pressure control, leak detection, and mixing destratification (T3).

Criterion #3: The extent to which information may lead to broad knowledge about exploration mission options (Impact on Exploration Efforts, Results in Improved Access to Data or to Samples)

Relevant research recommendations

Criterion #5: The extent to which the information gained is uniquely needed by NASA, as opposed to any other agencies (Needs Unique to NASA Exploration Programs)

Relevant research recommendations



POLICY EXAMPLE- LEADING EDGE SCIENCE

Goal: Develop new capabilities by advancing leading edge science



The second policy option is a decision to hold off on advanced human mission until we have developed a new base of capability with which to plan. This goal would focus near-term on advancing leading edge science and the value of our space assets to terrestrial needs. In this case, Prioritization Criteria #4 and #5 and #8 will have primary importance, and Prioritization Criteria #6 and #7 may also be of importance in building the integrated research portfolio which best supports this policy goal.

Criterion #4: The extent to which the information gained will fully or partially provide answers to grand science challenges for which the space environment provides a unique means to address (Relative Impact Within Research Field)

Establish a "microbial observatory" program on the ISS to conduct a long term multi-generational studies of microbial population dynamics.

Relevant research recommendations

Life sciences: P1, P2, B3, B4, AH9, AH10, AH11, AH16
Life sciences translational: CCH2, CCH6
Physical sciences: FP1, FP2, FP3, AP5, AP7, AP8, AP9
Physical sciences translational:

Criterion #5: The extent to which the information gained is uniquely needed by NASA, as opposed to any other agencies (Needs Unique to NASA Exploration Programs)

Microgravity provides a unique opportunity to study long-time dynamics of colloids, polymer and colloidal gels, foams, emulsions, and soap solutions free from gravitational interference

Relevant research recommendations

Criterion #8: The extent to which the information could result in either faster or better solutions to terrestrial problems or in terrestrial economic benefit (Ability to Translate Results to Terrestrial Needs)

Relevant research recommendations

Criterion #6: The extent to which the information gained can be synergistic with other agencies needs

Relevant research recommendations

Criterion #7: The extent to which the research must use the space environment to achieve useful information (Research Value of Using Reduced Gravity Environment)

Relevant research recommendations



HIGHEST PRIORITY RESEARCH RECOMMENDATIONS

PLANT AND MICROBIAL BIOLOGY

- Establish a “microbial observatory” program on the ISS to conduct a long term multi-generational studies of microbial population dynamics.
- Establish a robust spaceflight program of research analyzing plant and microbial growth and physiological responses to the multiple stimuli encountered in spaceflight environments.
- Develop a research program aimed at demonstrating the roles of microbial-plant systems in long-term life support systems.



HIGHEST PRIORITY RESEARCH RECOMMENDATIONS

BEHAVIOR AND MENTAL HEALTH

- Develop sensitive, meaningful, and valid measures of mission-relevant performance for both astronauts and ground crew.
- Conduct integrated translational research in which long duration missions are simulated specifically for the purpose of studying the interrelationship between individual functioning, cognitive performance, sleep and group dynamics.
- Determine the genetic, physiological and psychological underpinnings of individual differences in resilience to stressors likely encountered during extended space missions, with emphasis to develop a personalized approach to sustaining astronauts during such missions.
- Conduct research to enhance cohesiveness, team performance, and effectiveness of multinational crews, especially under conditions of extreme isolation and autonomy.



HIGHEST PRIORITY RESEARCH RECOMMENDATIONS

ANIMAL AND HUMAN BIOLOGY₁

- The efficacy of bisphosphonates should be tested in an adequate population of astronauts on the ISS during a 6- month mission.
- The preservation/reversibility of bone structure/strength should be evaluated when assessing countermeasures.
- Bone loss studies of genetically altered mice exposed to weightlessness are strongly recommended.
- New osteoporosis drugs under clinical development should be tested in animal models of weightlessness.
- Conduct studies to identify underlying mechanisms regulating net skeletal muscle protein balance and protein turnover during states of unloading and recovery.
- Studies should be done to develop and test new prototype exercise devices, and to optimize physical activity paradigms/prescriptions targeting multi-system countermeasures.
- Determine the daily levels and pattern of recruitment of flexor and extensor muscles of the neck, trunk, arms and legs at 1 g and after being in a novel gravitational environment for up to 6 months.



HIGHEST PRIORITY RESEARCH RECOMMENDATIONS

ANIMAL AND HUMAN BIOLOGY₂

- Determine the basic mechanisms, adaptations, and clinical significance of changes in regional vascular/interstitial pressures (Starling forces) during long duration space missions.
- Investigate the effect of prolonged periods of microgravity and partial ($3/8$ or $1/6$ G) gravity on the determinants of task specific, enabling levels of work capacity.
- Determine the integrative mechanisms of orthostatic intolerance after restoration of gravitational gradients (both 1 g and $3/8$ g).
- Collaborative studies among flight medicine and cardiovascular epidemiologists are recommended to determine the best screening strategies to avoid flying astronauts with subclinical coronary heart disease that could become manifest during a long duration exploration class mission (3 years).
- Determine the amount and site of the deposition of aerosols of different sizes in the lungs of humans and animals in microgravity.



HIGHEST PRIORITY RESEARCH RECOMMENDATIONS

ANIMAL AND HUMAN BIOLOGY₃

- Multiple parameters of T cell activation in cells should be obtained from astronauts before and after re-entry to establish which parameters are altered during flight.
- To both address the mechanism(s) of the changes in the immune system and to develop measures to limit the changes, data from multiple “organ/system-based” studies need to be integrated.
- Perform mouse studies, including immunization and challenge, with immune samples acquired both prior to and immediately upon re-entry on the ISS to establish the biological relevance of the changes observed in the immune system. Parameters examined need to be aligned with those influenced by flight in humans.
- Studies should be conducted on transmission across generations of structural and functional changes induced by exposure to space during development. Ground-based studies should be conducted to develop specialized habitats to support reproducing and developing rodents in space.



HIGHEST PRIORITY RESEARCH RECOMMENDATIONS

CROSS-CUTTING ISSUES FOR HUMANS IN THE SPACE ENVIRONMENT₁

- To ensure the safety of future commercial orbital and exploration crews, post-landing vertigo and orthostatic intolerance should be quantified in a sufficiently large sample of returning ISS crews, as part of the immediate post-flight medical exam.
- Determine whether artificial gravity is needed as a multi-system countermeasure, and whether continuous large radius AG is needed, or intermittent short radius AG is sufficient. Human studies in ground labs are essential to establish dose response relationships, and adequate gravity level, gradient, RPM, duration and frequency.
- Studies on humans are needed to determine whether there is an effect of gravity on micronucleation and/or intrapulmonary shunting, or whether the unexpectedly low DCS prevalence on Shuttle/ISS is due to underreporting and to determine operationally acceptable low suit pressure and hypobaric hypoxia limits.
- Optimizing dietary strategies for crews and food preservation strategies that will maintain bioavailability for 12 or more months.



HIGHEST PRIORITY RESEARCH RECOMMENDATIONS

CROSS-CUTTING ISSUES FOR HUMANS IN THE SPACE ENVIRONMENT₂

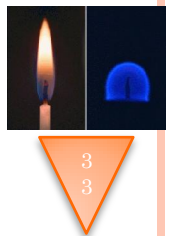
- Initiate a robust food science program focused on preserving nutrient stability for three or more years.
- Include food and energy intake as an outcome variable in intervention in studies in humans.
- Studies of astronauts for cataract incidence, quality, and pathology related to radiation exposures to understand risk from cataracts and to understand radiation-induced late tissue toxicities in humans.
- Conduct animal studies to assess radiation risks from cancer, cataracts, cardiovascular disease, neurologic dysfunction, degenerative diseases, and acute toxicities such as fever, nausea, bone marrow suppression, and others.
- Cellular ground-based studies to develop endpoints and markers that can be used to define acute and late radiation toxicities using radiation facilities that are able to mimic space radiation exposures.



HIGHEST PRIORITY RESEARCH RECOMMENDATIONS

CROSS-CUTTING ISSUES FOR HUMANS IN THE SPACE ENVIRONMENT₃

- Expand our understanding of gender differences in adaptation to the spaceflight environment through flight and ground based research, including potential differences in bone, muscle and cardiovascular function and long-term radiation risks.
- Investigate the biophysical principles of thermal balance to determine whether microgravity reduces the threshold for thermal intolerance.



HIGHEST PRIORITY RESEARCH RECOMMENDATIONS

FUNDAMENTAL PHYSICAL SCIENCES IN SPACE

- Research on complex fluids and soft matter.
- Understanding of the fundamental forces and symmetries of Nature.
- Research related to the physics and applications of quantum gases.
- Investigations of matter near a critical phase transition.



HIGHEST PRIORITY RESEARCH RECOMMENDATIONS

APPLIED PHYSICAL SCIENCES IN SPACE₁

- Reduced-gravity multiphase flows, cryogenics and heat transfer database and modeling, including phase separation and distribution (i.e., flow regimes), phase change heat transfer, pressure drop, and multiphase system stability.
- Interfacial flows and phenomena (including induced and spontaneous multiphase flows with or without phase change) relevant to storage and handling systems for cryogenics and other liquids, life support systems, power generation, thermal control systems, and other important multiphase systems.
- Dynamic granular material behavior and subsurface geotechnics to enable advanced human and robotic planetary surface exploration and habitation.
- Development of fundamentals-based strategies and methods for dust mitigation to enable advanced human and robotic exploration of planetary bodies.
- Experiments to understand complex fluid physics in a zero-gravity environment enabled by the ISS platform.



HIGHEST PRIORITY RESEARCH RECOMMENDATIONS

APPLIED PHYSICAL SCIENCES IN SPACE₂

- Fire safety research to improve methods for screening materials in terms of flammability and fire suppression in space environments.
- Combustion processes research, including reduced gravity experiments with longer durations, larger scales, new fuels, and practical aerospace materials relevant to future missions.
- Numerical simulation of combustion research to develop and validate detailed single and multiphase numerical combustion models.
- Materials synthesis and processing and control of microstructure and properties to improve the properties of existing and new materials on the ground.
- Design and develop advanced materials that meet new property requirements to enable human exploration at reduced cost using both current and novel materials synthesis and processing techniques and computational methods.
- Fundamental and applied research is required in developing technologies for extraction, synthesis, and processing of minerals, metals, and other materials available on extraterrestrial surfaces.



HIGHEST PRIORITY RESEARCH RECOMMENDATIONS

TRANSLATION TO SPACE EXPLORATION SYSTEMS₁

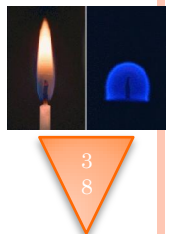
- Research should be conducted to address active two-phase flow questions relevant to thermal management.
- Research should be conducted in support of zero-boiloff propellant storage and cryogenic fluid management. Physical sciences research includes advanced insulation materials research, active cooling, multi-phase flows, and capillary effectiveness, as well as active and passive storage, fluid transfer, gauging, pressurization, pressure control, leak detection, and mixing destratification.
- NASA should enhance surface mobility; relevant research includes suited astronaut computational modeling, biomechanics analysis for partial gravity, robotic-human testing of advanced spacesuit joints and full body suits, and musculoskeletal modeling and suited range-of-motion studies (T4), and studies of the humanrobot interaction (including teleoperations) or the construction and operation of planetary surface habitats.



HIGHEST PRIORITY RESEARCH RECOMMENDATIONS

TRANSLATION TO SPACE EXPLORATION SYSTEMS₂

- NASA should develop and demonstrate technologies to mitigate the effects of dust on EVA systems and suits, life support systems, and surface construction systems. Supporting research includes impact mechanics of particulates, design of outer layer dust garments, advanced material and design concepts, magnetic repulsive technologies, and the quantification of plasma electrodynamic interactions with EVA systems; electrostatic coupling; and regolith mechanics and gravity-dependent soil models.
- NASA should define requirements for thermal control, micrometeoroid and orbital debris impact and protection, and radiation protection for EVA systems, rovers, and habitats and develop a plan for radiation shelters.
- NASA should conduct research for the development and demonstration of closed-loop life support systems and supporting technologies. Fundamental research includes heat and mass transfer in porous media under microgravity conditions and understanding the effect of variable gravity on multi-phase flow systems.
- NASA should develop and demonstrate technologies to support thermoregulation of habitats, rovers, and spacesuits on the lunar surface.



HIGHEST PRIORITY RESEARCH RECOMMENDATIONS

TRANSLATION TO SPACE EXPLORATION SYSTEMS₃

- NASA should perform critical fire safety research to develop new standards to qualify materials for flight and to improve fire and particle detectors. Supporting research is necessary in materials qualification for ignition, flame spread, and generation of toxic and/or corrosive gases and in the characterization of particle size from smoldering and flaming fires in microgravity.
- NASA should characterize the effectiveness of fire suppression and post-fire recovery strategies. Specific research is needed to develop and implement a standard methodology for qualifying fire suppression systems and to assess and restore a post-fire environment.
- Research should be conducted to allow regenerative fuelcell technologies to be demonstrated in reduced gravity environments.
- Research is needed to support the development of new energy conversion technologies. In particular, research is required for more efficient primary basepower and to enable the arrays for Solar Electric Propulsion to transfer large masses of propellant and cargo to distant locations.



HIGHEST PRIORITY RESEARCH RECOMMENDATIONS

TRANSLATION TO SPACE EXPLORATION SYSTEMS₄

- Research is needed in high-temperature, low-weight materials for power conversion and radiators to enable fission surface power systems.
- Development and demonstration of ascent and descent system technologies are needed, including ascent/descent propulsion technologies, inflatable aerodynamic decelerators, and supersonic retro propulsion system technologies. Research is needed in propellant ignition, flame stability, and active thermal control; lightweight flexible materials; and dynamics and control.
- Research is required to support the development and demonstration of space nuclear propulsion systems, including liquid-metal cooling under reduced gravity, thawing under reduced gravity, and system dynamics.
- Research is needed to identify and adapt excavation, extraction, preparation, handling, and processing techniques for a lunar water/oxygen extraction system.
- NASA should establish plans for surface operations, particularly ISRU capability development and surface habitats. Research is needed to characterize resources available at lunar and martian surface destinations and to define surface habitability systems design requirements.



FINAL COMMENTS

The committee and advisory panels have

- Defined the next decade of a science-based program that addresses, in an integrated fashion:
 - Plant and Microbial Biology
 - Behavior and Mental Health
 - Animal and Human Biology
 - Cross-cutting Issues for Humans in the Space Environment
 - Fundamental Physical Sciences in Space
 - Applied Physical Sciences in Space
 - Translation to Space Exploration Systems
- Developed metrics for prioritizing that research, and for creating timelines appropriate to policy decisions
- Addressed factors to strengthen the microgravity life and physical science enterprise and the translation of science to human exploration
- Recommended an integrated life and physical sciences research portfolio that:
 - Identifies facility and platform requirements
 - Provides rationale for all suggested program elements
 - Is adaptable to changes in policy and budget as they occur

